



Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at <http://about.jstor.org/participate-jstor/individuals/early-journal-content>.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

THE ORIGIN OF AUGITE ANDESITE AND OF RELATED ULTRA-BASIC ROCKS

REGINALD A. DALY
Massachusetts Institute of Technology, Boston

CONTENTS

INTRODUCTION.

TEMPERATURES AND ORDER OF CRYSTALLIZATION IN BASALT.

SINKING OF THE PHENOCRYSTS.

FORMATION OF ULTRA-BASIC MAGMAS AND OF AN ANDESITIC MOTHER-LIQUOR.

TESTS OF THE HYPOTHESIS.

1. Chemical relations.
2. Observed cases of sunken and risen phenocrysts.
3. Andesite actually observed to have been derived from basalt at an active volcano.
4. General field relations.
5. Relation of augite andesite to other andesites.
6. The rival hypothesis of magmatic differentiation.

SUMMARY AND CONCLUSION.

INTRODUCTION

Petrographers are in general agreement as to the existence of many close mineralogical and chemical similarities between augite andesite and basalt. It has, in fact, been found to be impossible to draw any sharp line between the two species. Nevertheless, the olivine basalts, volumetrically the most important class of lavas on the globe, are distinctly characterized by the great abundance of the basic phenocrysts, augite and olivine with which basic plagioclase and much magnetite are regularly associated as minerals of early generation. The list of phenocrysts in augite andesite normally includes the pyroxene and an average plagioclase which is more acid than that in the olivine basalts; olivine is absent and magnetite is less abundant than in the basalt.

These relations suggest the hypothesis that the andesite has been differentiated from the basalt by a process of fractional crystallization. This hypothesis is, in principle, nothing new, but it seems never to have been applied in detail to this particular pair of rock-species.

Vélain's observations at the isle of Réunion led him virtually to state the hypothesis, but, at the time of the publication of his memoir, very little was known as to the actual temperatures of crystallization in lavas, as to the degrees of fluidity which the lavas exhibit at those temperatures, nor as to the density of molten lava, phenocryst, or remelted phenocryst. It was, therefore, impossible for Vélain to show the exact conditions under which fractional crystallization can produce an andesitic lava from an original basalt. The experimental studies of the last twenty years have now made it possible to discuss the process of differentiation somewhat more fully.

It is one purpose of this paper to offer a brief statement of the hypothesis as viewed in the light of the experiments of Doelter and others on the properties of lavas during crystallization. A second purpose is to lay emphasis on the enormous scale in which this particular kind of differentiation of lavas has taken place. It appears to be a world-wide phenomenon. Thirdly, the hypothesis necessarily involves the correlative derivation of certain ultra-basic lavas and rocks from olivine basalt. The conception has thus become of practical value to the writer in helping to explain the recurrent field-association of olivine basalt, augite andesite, and various peridotitic rocks discovered in the Selkirk, Columbia, and Cascade mountain-ranges of British Columbia. The hypothesis will here be presented in a general form, for, while it appears to explain the field-occurrences actually studied by the writer, the conception, like all petrogenic hypotheses, should stand the test of geological experience throughout the world.

TEMPERATURES AND ORDER OF CRYSTALLIZATION IN BASALT

As a result of numerous experiments on artificial basic melts and on natural lavas, as observed under the microscope, Doelter has proved that olivine, augite, magnetite, and plagioclase crystallize in the order which has been deduced from the microscopic study of basalt by Rosenbusch, Zirkel, and other systematic petrographers.¹

According to Doelter, both magnetite and phenocrystic olivine crystallize from artificial basic melts at temperatures ranging between 1200° and 1030° C. The olivine largely crystallizes between 1200°

¹ C. Doelter, "Die Silikatschmelzen," *Sitzungsberichte der k. Akad. d. Wissen.*, Vienna, Math.-naturw. Klasse, Bd. 103, 1904, p. 177.

and 1135° C.; the magnetite, largely between 1195° and 1100° C. The range for phenocrystic augite is 1190–960° C., with the most abundant crystallization between 1190° and 1100° C. The range for labradorite is 1125°–1075° C. He observed augite phenocrysts developed in molten basalt at the range, 1085°–920° C.; in molten limburgite at 1150°. Magnetite formed abundantly in molten basalt at 1095° C. and in molten limburgite at various temperatures ranging from 1170° to 1065° C. For rock-melts he records only one determination for olivine which “probably” crystallized out at 1085° C. in molten basalt.

Throughout most of the period of phenocrystic development, that is, through a fall of temperature from 1200° to about 1080° C., basaltic lava is still notably fluid. Other experiments by Doelter have shown that strong fluidity characterizes various basic lavas at the following respective temperatures:

Etna basalt	1010° C.
Remagen basalt	1060
Vesuvian lava	1080
Limburgite	1050

It is fair to conclude that at the temperature of 1050° C. the average olivine basalt is fluid, and at 1100° C. quite thinly fluid. At the latter temperature its kinetic viscosity is probably comparable to that of the Hawaiian basaltic flow which Becker has calculated to have had, at the time of its emission, a viscosity about fifty times that of water.¹

SINKING OF THE PHENOCRYSTS

In lava of such relatively high fluidity the olivine, augite, and magnetite crystals must slowly sink. Combining the results obtained by C. Barus² and, more recently, by J. A. Douglas,³ on studies of volume changes as basic rock changes from the holocrystalline state to the glassy and then to the molten condition, the present writer has calculated that olivine basalt would have, at 1100° C. and at one atmosphere of pressure, a specific gravity averaging about 2.74; its groundmass, specific gravity ranging from 2.55 to 2.60. At the

¹ G. F. Becker, *Amer. Jour. of Sci.*, Vol. III, 1897, p. 29.

² *Bull. No. 103*, U. S. Geological Survey, 1893.

³ *Quart. Jour. Geol.*, Vol. LXIII, 1907, p. 145.

same temperature crystals of olivine (3.40), augite (3.30), magnetite (5.00), labradorite (2.70), and anorthite (2.75) would have specific gravities of, respectively, about 3.30, 3.20, 4.85, 2.61 and 2.66. These values are only approximate, but they show the order of the density differences to be expected between the phenocrysts and their mother-liquor. It appears probable that all the crystals except labradorite would slowly sink in the mother-liquor.

Some idea can be obtained of the rate at which the heavier phenocrysts would sink. For a spherical body the velocity of subsidence (x) at a time when steady motion is reached in a highly viscous fluid, may be found by solving the equation:

$$x = \frac{2g}{9} \times \frac{r^2(d-d')}{v},$$

where g = the acceleration of gravity; r , the radius of the sphere; d , the density of the body; d' , the density of the fluid; v = viscosity.¹ This equation has been experimentally verified by Ladenburg who found that steel spheres, ranging from about 0.075 to about 0.2 cm. in radius took, respectively, from 570 seconds to 3,858 seconds to fall through a 20-centimeter column of Venetian turpentine—a substance a hundred thousand times more viscous than water.²

In an experiment by Jamin, pieces of stone sank through a layer of pitch in the course of several days (quelques jours), and corks simultaneously rose through the pitch, which, at 6° C, is much over 1,000,000,000,000 times as viscous as water.³

It is thus clear that even if the viscosity of the lava, within the temperature interval of early phenocrystic development, be many thousand times that of water, the phenocrysts must tend to sink. So long as such a crystallizing lava-column remains in its conduit and there undergoes cooling through the temperature interval, 1200°–1050° C.—a process necessarily involving a long period of time—the settling of the magnetite, olivine, and augite crystals will continue, though at a continuously slower rate. Theoretically the settlement

¹ Cf. Poynting and Thomson, *Textbook of Physics, Properties of Matter*. (London, 1902), p. 222.

² R. Ladenburg, *Annalen der Physik*, Vol. XXII, 1907, p. 287.

³ Jamin et Bouty, *Cours de Physique* (Paris, 1888), Tome 1. 2^e fascicule, 1888, p. 135.

will continue during the time occupied in the drop of temperature of another 100°C. or to the point when practical rigidity is established; but the rate of settlement must then be very considerably slower than in the interval, $1200^{\circ}\text{—}1050^{\circ}\text{C.}$ During the last-mentioned interval practically all of the olivine, much of the phenocrystic augite, and much of the magnetite of early generation has settled out of the upper part of the lava-column. Below 1050°C. the mother-liquor crystallizes. New crystals of magnetite and phenocrysts of augite and feldspar are formed but, because of the greatly increased viscosity, do not sensibly sink or rise in the freezing melt.

To estimate the chemical composition of the mother-liquor it would be necessary to know the composition of the original basalt and the quantity and composition of each settled-out phenocrystic material. The problem may be solved through a careful quantitative chemical study of a typical olivine basalt; the results are of the same order as those obtained from a comparison between the average compositions of the world's olivine basalt and of its phenocrysts. The result of these comparisons will be detailed on a later page.

FORMATION OF ULTRA-BASIC MAGMAS AND OF AN ANDESITIC MOTHER-LIQUOR

As the phenocrysts sink they enter levels in the conduit where the temperature is higher than near the surface, and where the basalt is as yet completely molten. Probably the lava-column grows slightly more dense toward its base, according to faint chemical differences in the successive strata. The sunk phenocrysts, at the lower levels and higher temperatures will, in turn, become re-dissolved or melted. Deville,¹ Doelter² and others have shown that both olivine and augite expand extraordinarily in passing from the crystalline state to the glassy. The specific gravities of a few typical specimens at room temperatures are indicated in the following table:

	Crystal	Glass	Molten at 1200°C.
Augite (Doelter).....	3.30	2.92	2.83
Augite (Deville).....	3.267	2.803	2.72
Olivine (Deville).....	3.381	2.831	2.75

¹ Cf. F. Zirkel, *Lehrbuch der Petrographie* (Leipzig, 2d ed., 1893), Vol. I, p. 680.

² C. Doelter, *Physikalisch-chemische Mineralogie* (Leipzig, 1905), p. 8.

Each of these glasses would expand, with heating, at least as fast as diabase, e.g., 3 per cent. for 1200°C . (Barus). At 1200°C ., therefore, the remelted crystals would have specific gravities at least as low as the values shown in the third column. The specific gravity of normal basalt at 1200°C . for a type which is holocrystalline at specific gravity of 3.00, is about 2.74; that for a type holocrystalline at 3.10 is about 2.83—both these values being calculated from the data of Barus and Douglas. There seems to be good reason to believe, therefore, that the remelted and more or less perfectly dissolved phenocrysts would not sink indefinitely deep in the lava column, but would come to rest, forming one or more ultra-basic layers in the conduit.

In an active volcano the time allowed for the growth and sinking of phenocrysts may be long enough for a complete differentiation, or it may suffice only to remove some of the olivine and magnetite from the cooling surface layer of the column, or it may be so short as to forbid the growth of phenocrysts in the vent. Eruption will necessarily arrest or greatly retard the process. Where the outflow is rapid and continuous the original olivine basalt appears at the earth's surface. There, of course, the rapid cooling generally prevents recognizable differentiation in the way possible, and, apparently necessary, in the vent itself when the basalt stands within it for a considerable time.

We have, then, to expect in nature a continuously graded series of lavas from pure olivine basalt, through olivine-free basalt, to those phases of the mother-liquor which must approximate a basic augite andesite and then an acid augite andesite. The last rock would thus represent the one phase, the more voluminous phase, of this kind of differentiation. In view of the notably uniform composition of olivine basalts throughout the world we must further expect, that, in all cases where the fractional crystallization has run a complete course, the more acid phase should be relatively uniform in chemical composition. Its phenocrysts form when the magma's viscosity is relatively high and sinking is very slow.

The other products of the differentiation must also show a very great variation in composition. According to the special thermal conditions and shape of each lava-column, the phenocrysts must sink

to different depths, and be segregated or dissolved in highly different proportions in different levels of the lava-column. From the original olivine basalt many types of ultra-basic basaltic magma and of peridotitic magma might be developed in the same conduit. During energetic eruption or intrusion into the walls of the conduit these might become mixed with each other and the resulting rocks present just such great variation as is actually observed in the peridotite family. Many peridotites, the picrites, limburgites (magma basalts), and abnormally olivinitic basalts are, in this view, the rocks derived from the fractional crystallization of olivine basalt, while augite andesite represents the other pole of the differentiation.

TESTS OF THE HYPOTHESIS

1. *Chemical relations.*—The view that olivine basalt may be the parent of augite andesite and of several ultra-basic igneous types is well supported by a comparison of Streng's total analysis of a dolerite and his analysis of its own glassy base.¹ The two are here quoted.

	Dolerite	Glassy base
SO ₂	49.08	55.15
TiO ₂	1.82	2.05
Al ₂ O ₃	13.43	15.37
Fe ₂ O ₃	6.49	4.66
FeO.....	5.92	5.73
MgO.....	9.58	4.20
CaO.....	8.92	7.62
Na ₂ O.....	3.42	3.45
K ₂ O.....	1.00	0.74
H ₂ O.....	0.32	0.80
P ₂ O ₅	0.51	
	100.49	99.77

The phenocrysts of the dolerite include andesine, augite, enstatite, and olivine; and magnetite is, of course, a noteworthy constituent. The composition of the glassy base clearly tends toward that of an augite andesite, though the whole possible amount of phenocrystic development was, in the case of this dolerite, not attained. Streng observed that the phenocrysts were largely or altogether wanting in the upper-surface layer of the dolerite flow, but he thought it "improbable" that their absence was due to settlement of the crystals. He attributed the phenomenon rather to the operation of Soret's principle,

¹ *Neues Jahr. für Min., etc.*, 1888(2), p. 211.

the flow having undergone true magmatic splitting under the influence of a maximum rate of cooling at the surface. As a result of the magmatic differentiation the lava crystallized differently near the surface and within the main body of the flow. To petrologists of the present day this view must seem highly improbable, as it involves an impossible speed of molecular diffusion. The alternative view, rejected by Streng, that the andesitic, phenocryst-free surface phase is due to settlement of the olivine and pyroxene, certainly seems more worthy of belief.

Secondly, the hypothesis of fractional crystallization might be tested by a comparison of the analyses of the world's average olivine basalt, augite andesite, and ultra-basic rocks, along with the average analysis of each of the staple phenocrysts in olivine basalt. An approximation to most of these averages has been made possible through Osann's great compilation of the rock-analyses made between the years 1884 and 1900.¹ From his tables an average of all the available typical analyses for each rock-species has been calculated by the present writer.

In Table I, Column 1, the average composition of 161 typical basalts (largely olivine-bearing), is entered. In Columns 2 to 6 are entered, in order, the average compositions of 11 Hawaiian basalts, 17 olivine diabases, 9 dolerites, 11 melaphyres, and 17 olivine gabbros. In Column 7 is entered the average of the 198 analyses which include all but the olivine gabbros. Since some of the basalts are olivine-free (perhaps through settling out of the phenocryst) it seems probable that the addition of the 17 olivine gabbro analyses to the average total would render it more nearly representative of the true world-average than that shown in Column 7.

Column 8 of Table II indicates the result of averaging all 215 analyses given in partial averages in Columns 1, 3, 4, 5 and 6, Table I, and hence represents rather closely the mean composition of olivine basalt throughout the world.

Column 9 gives the result of averaging 33 of the most typical augite andesites in Osann's compilation. Columns 10, 11, and 12 give the similar averages of, respectively, 49 peridotites, 7 limburgites and 3 picrites.

¹ A. Osann, *Beiträge zur chemischen Petrographie*, Part 2, Stuttgart, 1905.

TABLE I
AVERAGE ANALYSES—BASALTS AND ALLIED ROCKS

	1 All Basalt	2 Hawaiian Basalt	3 Olivine Diabase	4 Dolerite	5 Melaphyre	6 Olivine Gabbro	7 First General Average
SiO ₂	48.78	48.36	50.10	49.50	50.60	46.49	49.06
TiO ₂	1.39	0.66	1.25	1.42	0.68	1.17	1.36
Al ₂ O ₃	15.85	15.40	14.43	14.37	17.40	17.73	15.70
Fe ₂ O ₃	5.37	6.48	5.06	6.55	4.57	3.66	5.38
FeO.....	6.34	10.07	6.31	5.84	6.29	6.17	6.37
MnO.....	0.29	0.80	0.25	0.17	0.46	0.17	0.31
MgO.....	6.03	4.19	7.32	7.75	4.89	8.86	6.17
CaO.....	8.91	8.69	9.53	9.96	8.09	11.48	8.95
Na ₂ O.....	3.18	3.34	2.75	2.50	3.23	2.16	3.11
K ₂ O.....	1.63	1.30	0.73	0.84	1.76	0.78	1.52
H ₂ O below 110° C	0.73	} 0.43	2.00	{ 0.29	1.83	0.18	{ 1.62
H ₂ O above 110° C	1.03						
P ₂ O ₅	0.47	0.28	0.27	0.44	0.20	0.29	0.45
No. of analyses ..	161	11	17	9	11	17	198

Sum, 100.00 in each case.

Sum, 100.00 in all analyses.

TABLE II
AVERAGE AUGITE ANDESITE, OLIVINE BASALT, PERIDOTITE, LIMBURGITE AND
PICRITE

	8 Second General Average Olivine Basalt	9 Augite Andesite	10 Peridotite	11 Limburgite	12 Picrite
SiO ₂	48.84	57.50	44.39	41.69	43.24
TiO ₂	1.35	0.79	0.88	0.67	.....
Al ₂ O ₃	15.90	17.33	5.14	14.80	15.19
Fe ₂ O ₃	5.23	3.78	3.88	} 15.04	{ 8.62
FeO.....	6.30	3.62	6.70		
MnO.....	.29	0.22	0.19	.....	.....
MgO.....	6.38	2.86	29.17	8.64	8.56
CaO.....	9.15	5.83	6.31	11.98	13.78
Na ₂ O.....	3.05	3.53	0.64	3.52	0.54
K ₂ O.....	1.46	2.36	0.76	1.17	0.48
H ₂ O.....	1.60	1.88	1.80	2.36	1.21
P ₂ O ₅	0.45	0.30	0.14	0.13	0.49
No. of analyses.....	215	33	49	7	3

Sum, 100.00 in each case.

All of these averages were made after the method of Washington and Clarke in their latest determinations of the average rock-analysis for the world. Thus, the average for each oxide is based only on the

actual number of its determinations in the respective group; "trace" is taken to mean 0.01 per cent.

For the purpose of making a fair comparison among these averages it is necessary to recalculate them all as anhydrous; for, clearly, a large, though unknown, fraction of the water entered in the hundreds of analyses, must be regarded as mechanically absorbed water.

Table III, Columns 13, 14, 15, 16, and 17, shows these recalculated averages.

TABLE III
RECALCULATED AVERAGES, WATER EXCLUDED

	13 Olivine Basalt	14 Augite Andesite	15 Peridotite	16 Limburgite	17 Picrite
SiO ₂	49.65	58.65	45.20	42.69	43.77
TiO ₂	1.37	0.80	0.90	0.68	.....
Al ₂ O ₃	16.16	17.67	5.25	15.18	15.37
Fe ₂ O ₃	5.31	3.85	3.95	15.43	8.72
FeO.....	6.40	3.69	6.82		
MnO.....	0.29	0.22	0.19	.....	.....
MgO.....	6.48	2.90	29.70	8.85	8.66
CaO.....	9.30	5.92	6.43	12.27	13.95
Na ₂ O.....	3.10	3.60	0.65	3.58	0.55
K ₂ O.....	1.48	2.40	0.77	1.19	0.49
P ₂ O ₅	0.46	0.30	0.14	0.13	0.50

Sum, 100.00 in each case.

Table IV, Column 18, indicates the average composition of the olivine phenocrysts in basalt, according to Rammelsberg.¹ Column

TABLE IV
COMPOSITION OF PHENOCRYSTS IN OLIVINE BASALT

	18 Olivine (Rammelsberg)	19 Augite	20 Labradorite (Ab ₁ An ₁)	21 Anorthite
SiO ₂	41.01	47.72	55.55	43.16
TiO ₂.....	.....	1.10	.....	.....
Al ₂ O ₃.....	.....	6.31	28.35	36.72
Fe ₂ O ₃.....	.....	3.12	.....	.....
FeO.....	9.83	5.31	.....	.....
MnO.....	.....	0.50	.....	.....
MgO.....	49.16	14.01	.....	.....
CaO.....	.....	20.71	10.36	20.12
Na ₂ O.....	.....	0.80	5.74	.....
K ₂ O.....	.....	0.42	.....	.....
Sp. gr. of crystal.....	ca. 3.40	ca. 3.30	2.700	2.75

¹ Quoted in Zirkel's *Lehrbuch der Petrographie*, 2d ed. (1893), Vol. I, p. 353.

19 gives the result of averaging 14 analyses of augite phenocrysts from basalt, dolerite, limburgite, and labradorite porphyrite, as stated in the appendix to Osann's compilation. Columns 20 and 21 represent typical analyses of labradorite and anorthite respectively.

By the settling-out of olivine, augite, and magnetite the molten lava or mother-liquor, must, when compared with the original basalt, be poorer in iron oxides, magnesia and lime, and richer in silica, alumina and the alkalis. The change in alumina might be slight, provided that the anorthite phenocrysts also settled out. Crystals of labradorite and andesine would slowly rise and enrich the upper part of the lava-column with silica, alumina, and soda. Chemically the average augite andesite appears to correspond to the mother-liquor, possibly bearing up-floated plagioclase crystals, while many of the ultra-basic rocks, picrite, limburgite, dunite, harzburgite, and other peridotites, correspond to those magmatic types developed deep within the lava-column by the settling of the phenocrysts.

2. *Observed cases of sunken and risen phenocrysts.*—A few instances of gravity differentiation accompanying the growth of phenocrysts in magma have been observed in rocks and also in artificial melts. Both Scrope, in 1825, and Charles Darwin, in 1844, published hypotheses, now classic, of such fractional crystallization in nature. Clarence King, in 1878, adopted their conclusion and added new examples studied by him at Kilauea. He broke asunder some of the thin, tongue-like flows of once very fluid basalt and found that in every case the bottom of the flow was thickly crowded with triclinic feldspars and augites, while the whole upper part of the stream was of nearly pure isotropic and acid glass.¹ He further remarked on the general absence of phenocrysts in some of the great Hawaiian flows; the crystals sank away into the conduit before eruption. Certain other Hawaiian flows described by E. S. Dana show the complementary feature of being ultra-basic and crowded with olivine crystals, which make up as much as 50 per cent. of the rock.² Neither at Kilauea nor at Mauna Loa, however, would one expect to find a notable differentiation of augite andesite. The extreme fluidity of lava-columns in both of the great pits seems to indicate general tempera-

¹ *U. S. Geol. Explor. 40th Parallel*, Sys. Geol., 1878, p. 716.

² J. D. Dana, *Characteristics of Volcanoes* (New York, 1891), p. 324.

tures above those at which even olivine can form. The "white" heat of the huge lava-fountains corresponds to a temperature of 1300° C. or over.¹ Granting that the Hawaiian conduits have always been so much superheated, it is not surprising that so few types of lava, other than olivine basalt, have been found on the island.

Iddings has described a striking case of the sinking of the augite phenocrysts, enriching a thick layer at the bottom of a 30-foot intrusive sheet on Electric Peak, Yellowstone Park.² It is not clear why so thin a sheet should have been differentiated and thus stand in contrast to hundreds of mapped sills of at least as great thickness, in which no differentiation is visible. Possibly the explanation is to be found in the fact that the Electric Peak sill is unusually rich in sulphur trioxide, chlorine, lithia, and "combined" water—substances which tend to lower the viscosity of magmas. In this case, though the magma was rather quickly chilled against the inclosing shales, the dissolved volatile matter maintained the fluidity long enough for the phenocrysts to fall to the bottom.

Against the hypothesis of fractional crystallization and gravitative sinking, it might be objected that the heavy minerals of early generation in gabbros and other plutonic types which have crystallized under slow-cooling conditions, are generally quite uniformly distributed through rock and show no concentration by gravity. There are, however, good reasons to believe that each plutonic magma, before any crystallization begins, is regularly cooled down several hundred degrees of the Centigrade scale below the melting-point of the rock resulting from the crystallization of the magma. The experiments of Oetling³ and Amagat⁴ show that pressure is a principal cause of this retardation of crystallization. According to Vélain⁵ the retention of the volatile solvents, such as chlorides, would further tend to lower the temperature of crystallization in depth, while their escape at a volcanic vent would allow crystals to form at a higher

¹ Cf. H. Le Chatelier and O. Boudonard, *High Temperature Measurements*, trans. by G. Burgess, New York, 1904, p. 246.

² *Monograph* 32, Pt. 2, U. S. Geol. Surv., 1899, p. 82.

³ *Tscher. min. u. petrog. Mitt.*, Vol. XVII, 1897, p. 332.

⁴ *Comptes Rendus*, No. 16, 1893.

⁵ *Op. cit.*, p. 181.

temperature and therefore during a less viscous stage of the magma's history. In an under-cooled silicate melt crystals must sink but slowly.

The crystallization of most plutonic magmas and of lavas at the earth's surface are thus believed to take place under strongly contrasted conditions. At the surface of a lava-column olivine, magnetite, augite, and plagioclase begin to form at high temperatures, when the viscosity is relatively low; the time-interval of crystallization for the whole magma is relatively long. Under plutonic conditions the same minerals crystallize at lower temperatures, when high viscosity is established and (because of under-cooling) the time-interval of crystallization is probably short.

Nevertheless, in some plutonic bodies of large size a certain amount of fractional crystallization and settlement of basic minerals may have actually taken place. Kemp has suggested that the anorthosites of the Adirondacks have been derived from more normal gabbro as a result of the sinking of the heavy constituents, either crystallized or still molten. He considers that the titaniferous magnetites of the region were erupted into the anorthosite after the anorthosite had consolidated, and implies that the molten ore has been derived from a *couche* which was formed from settled-out magnetite.¹ The relation of anorthosite and magnetite would, thus, be analogous to that postulated between augite andesite and certain olivine-rocks. Secondly, it is further possible that many basic contact-zones represent those parts of the respective intrusive masses where, on account of the relatively rapid cooling, the settling of basic minerals has been specially restrained, while the process has notably affected the composition of the slower-cooling interior of each mass. According to Kemp and Cushing² the huge anorthosite masses of the Adirondacks are characterized by wide contact-zones of rock relatively rich in pyroxene and magnetite (gabbro and anorthosite-gabbro). This gabbroid phase is usually finer grained and was presumably chilled more rapidly than the main body of the anorthosite.

¹ *Nineteenth Annual Report*, U. S. Geological Survey, pt. 3, 1899, p. 417.

² H. P. Cushing, *Geology of Franklin County*, 18th Report of the State Geologist (Albany, 1900), p. 101; *New York State Museum Bull. No. 95* (1905), p. 305 and *Bull. 115* (1907), p. 471.

It is obvious that the gravity-separation of phenocrysts in lava which has once escaped from its conduit and then cooled rapidly, will not be conspicuous in the average flow. The separation will be most pronounced in the upper levels of an active volcanic neck or lava-filled fissure.

The rising of phenocrysts in magma more dense than themselves has seldom been actually observed, partly for the reason that few phenocrysts are lighter than their matrix. Mercalli has described a case of the concentration of leucite phenocrysts (sp. gr. at 1100° C. about 2.42) in the surface layer of an 1883 flow of Vesuvian lava (sp. gr. molten at 1100° C. about 2.70).¹ An analogous instance is recorded by Morozewicz who found that tridymite (sp. gr. at 1300° C. 2.24), derived from converted quartz grains, floated to the top of a crucible in which he had melted two pounds of granite (sp. gr. at 1300° C. about 2.40).²

3. *Andesite actually observed to have been derived from basalt at an active volcano.*—But all deductive argument for the hypothesis must, in order to be entirely convincing, be supplemented with the positive facts of the field. The great value of Vélain's discovery in the Île de la Réunion (Bourbon) has surely never been adequately recognized in discussions on the origin of magmas.³ A few weeks before his party reached Réunion the 8000-foot volcano at the southeastern end of the island erupted fluid lava at its summit and, simultaneously, other lava issued from a fissure on the flank of the volcano, a fissure which communicated with the main vent.

The lava issuing at the summit was relatively acid and had a composition apparently similar to that of the lava collected at the summit in the walls of the crater itself. The latter was analyzed by Vélain, with the following result:

SiO ₂	. . . . .	57.49	Na ₂ O	. . . . .	3.64
Al ₂ O ₃	. . . . .	16.41	K ₂ O	. . . . .	2.92
FeO	. . . . .	10.65	Loss on ignition	. . . . .	0.13
MnO	. . . . .	0.06			
MgO	. . . . .	1.23			100.05
CaO	. . . . .	7.52	Sp. gr.	. . . . .	2.79

¹ *Atti della Soc. ital. di scienze nat.*, Vol. XXVII, 1884.

² *Tscher. min. u. petrog. Mitt.*, Vol. XVIII, 1898, p. 332.

³ C. Vélain, *Mission de l'île Saint-Paul* (Paris, 1888), pp. 101 ff.

This rock appeared to be quite holocrystalline and was essentially composed of feldspar microclites, augite and iron oxide; olivine was a rare accessory. The augite and feldspar appear in large part to have crystallized at the same time.

The lava from the flanking fissure was examined and found to be very dense (sp. gr. 2.97) and much more basic than the lavas at the edge of the crater "qui datent pourtant de la même phase éruptive." This basic lava carried only 48.98 per cent of silica. It is rich in olivine, magnetite and augite, with which less abundant crystals of anorthite are associated.

Ainsi, déversement d'une lave vitreuse, relativement riche en silice, par-dessus les bords du cratère comme un trop-plein, puis soutirage par des crevasses latérales, ouvertes à une assez grande distance du sommet, d'une lava tout à la fois plus basique et plus dense, chargée de péridot, mais se rapprochant de la précédente par la nature de son élément feldspathique (anorthite), tels sont les deux phénomènes consécutifs présentés par l'éruption de 1874. On peut les considérer comme représentant la marche habituelle des éruptions de ce volcan.¹

The basic lava was observed to flow slowly, so that one may conclude that the temperature was well below 1200° C. or the point at which olivine begins to form in a cooling basalt. Other recorded flows of basaltic nature, such as that of 1812, ran with great speed, indicating higher temperatures and much lower kinetic viscosity. The temperature of the lavas within the vent is, thus, sufficiently variable to allow of their intermittent differentiation by the sinking of phenocrysts. In the process of time the island has been built up by alternating flows of olivine basalt, basic and acid augite andesites, and either true picritic rocks (described by Vélain) or their near relatives, ultra-basic basalts. Normal olivine basalt formed the original lava, whence, through fractional crystallization, the other types were derived.

4. *General field relations.*—The hypothesis implies that, in general, the derivation of augite andesite and olivine rocks from olivine basalt takes place in the relatively small openings represented by volcanic vents; secondly, that the effective differentiation occurs only when the lava column stands in the vent for a considerable time, and at temperatures ranging between 1200° and 1050° C.; thirdly, that the peri-

¹ C. Vélain, *op. cit.*, p. 182.

dotitic, limburgitic or picritic magma resulting from the remelting of the settled phenocrysts, would form at the base of the lava-column and would be considerably smaller in volume than the correlative andesite; fourthly, that the heavy, ultra-basic magma would oftener form intrusive than extrusive rocks, and would fill fissures either in the basal beds of the cone itself or in the older formations on which the cone rests; fifthly, that the primary basaltic magma is directly represented on the earth's surface where the lava was erupted rapidly in great volume, and at such temperatures that the phenocrysts of large size had not yet formed in abundance; and, sixthly, that augite andesite would be most often developed in and about the great volcanic cones, in the building of which the physical conditions and the duration of eruption were appropriate for pronounced fractional crystallization.

These various implications seem to be fairly matched by the facts of rock-distribution and rock-occurrence. The whole group of rocks here considered—basalts, andesites, peridotites, picrites, limburgites, etc., are consanguineous and several of them are commonly associated in the field. Where some of the derivatives are lacking in the existing outcrops, as in some of the British Columbia cases, the others may have been eroded away, or, on the other hand, have not yet been revealed by erosion. The ultrabasic rocks never form bodies of batholithic size but form dikes, sheets, "chonoliths,"¹ etc., and are thus always in such development as is explicable on this hypothesis. They form injected, not subjacent bodies. The olivine basalts are most largely developed in the vast lava-fields of the fissure-eruption type, where the emission of the primary lava has been too rapid for differentiation in the fissures. Augite andesite is most characteristically found in and about the greater cones, like those of the Andes mountain system or like most of the hundreds of very lofty cones rising from the floor of the deep sea. It has been already pointed out that the Hawaiian volcanoes carry superheated lavas, which, on account of the high temperature of the main body of each lava-column, cannot usually undergo pronounced fractional crystallization; yet the studies of J. D. and E. S. Dana show that some separation into olivine-free basalt and ultra-basic basalt has taken place before some of the

¹ *Journal of Geology*, Vol. XIII, 1905, p. 485 ff.

eruptions. King's observations warrant the belief that some differentiation by fractional crystallization occurs in the lava after it escapes from the calderas of Hawaii. However, the Hawaiian rocks are more allied to those of an Idaho or Oregon lava-flood than to the typical andesites of Ecuador. The poverty of Etna lava in phenocrysts may be explained as due to the partial differentiation of the primary olivine basalt.¹

5. *Relation of augite andesite to other andesites.*—The hypothesis has been framed on the supposition that the primary basaltic magma has not been essentially affected by its solution or assimilation of chemically contrasted rock, material with which the lava makes contact as it rises or lies in the volcanic conduit. It is, however, most probable that the primary lava may in many cases absorb a certain amount of foreign material, either rock or fluid, and that the products of fractional crystallization must then vary notably from the few types so far mentioned. The process itself may be aided or retarded by such absorption, according as the absorption affects the temperatures of crystallization or the viscosity. Phenocrysts and ground-mass must change in chemical composition. Their separation by gravity would, then, produce magmatic materials not directly corresponding to augite andesite nor to any of the ultra-basic rocks formed directly from olivine basalt.

Hornblende andesites, mica andesites, dacites, etc., may, on this view, be derivatives of the primary basalt which has been modified by the assimilation of foreign rock-substance; while certain of the peridotites may represent some of the correlative differentiates of the compound lava. In a similar manner, one might possibly consider many lamprophyres and aplites as due to the analogous differentiation of their respective parent-magmas by the settling of basic minerals from the latter in its magmatic condition. It is not here the writer's purpose to discuss these possibilities in detail; they are noted rather to point to his belief that the commonly observed field associations and chemical relationships of augite andesite and other andesites are facts not opposed to the hypothesis outlined. It is, however, by no means intended to express the belief that *all* andesites or *all*

¹ Cf. H. Rosenbusch, *Mikros. Physiographie der massigen Gesteine*, 3d ed. (Leipzig, 1896), p. 1011.

peridotites have been formed through gravity separation of basic minerals; such a view is manifestly wrong.

6. *The rival hypothesis of magmatic differentiation.*—Finally, the hypothesis should meet the test of showing superiority over an obvious alternative suggestion. It might be conceived that augite andesite is due to the splitting of the basaltic magma before crystallization set in. In this view one must suppose that the splitting is due to a drastic change of physical conditions when the lava passes from abyssal levels to levels at or near the surface. The pressure is certainly very different in the two positions. However, no facts are in hand to show that a release of pressure causes immiscibility between two such magmas as molten andesite and molten peridotite, the two actually observed differentiates. If release of pressure alone caused the spontaneous splitting of olivine basalt into lighter andesite and heavier peridotite, we should very rarely expect to find true olivine basalt on the earth's surface, for most of these fluid lavas spend a considerable time in their conduits before being erupted. Against the idea is, further, the absence of any known physical reason why release of pressure should cause immiscibility. Experiments seem, on the contrary, to show that increase of pressure tends to promote immiscibility.

Immiscibility might conceivably ensue through a fall of temperature from a superheated condition, but there is no direct evidence that the phenomenon has a place in the history of volcanic cones or fissure-vents.

However probable may be the doctrine of immiscibility for certain magmas under plutonic conditions, we may regard the evidence on the problem as negative so far as volcanoes are concerned. The case may be summed up thus: The basaltic magma *may* split spontaneously into two or more magmas at a volcanic vent, but the phenocrysts of a molten basalt *must* sink while the lava undergoes the extremely slow cooling within the vent. Possibly both methods of differentiation are active. For the one advocated specially in this paper the physical conditions are quite simple and are largely understood quantitatively. The alternative view is at present a somewhat elusive conception for the petrologist and has few field-observations or compelling deductive considerations in its favor. It should, however; be added that the

writer believes in magmatic splitting under other conditions than those at the crater of a basalt volcano. Either hypothesis will, of course, recognize augite andesite as a derivative from olivine basalt; the balance of probability is here attributed to the hypothesis of fractional crystallization.

SUMMARY AND CONCLUSION

The purpose of the writer has been to state the results of correlating many scattered items of fact derived from experimental and field studies. The correlation seems strongly to support the early views of Scrope, Darwin, and others as to the efficiency of fractional crystallization in the formation of igneous rocks. It is only quite recently that this general hypothesis could be put on a quantitative basis. Even now there are needed many additional physical and chemical determinations before the hypothesis can reach its full measure of conviction for the petrologist. Nevertheless a compilation of the already established facts seems to show that the idea of rock-differentiation by the gravitative separation of certain minerals gains greatly in meaning, force, and usefulness when applied to actual rock-types and to actual petrographical provinces.

The hypothesis explains the origin of a considerable number of igneous rock-types. Augite andesite and many olivine-free basalts form what may be called one pole of the differentiation of olivine basalt. Picrite, limburgite, many peridotites and other ultra-basic types form the other polar group of differentiates. The conditions for the differentiation in the typical and general case, involve, in each case, a somewhat prolonged residence of the primary basalt in a volcanic vent in which the temperature varies from about 1200° to about 1050° C. The phenocrysts formed in the lava at these temperatures, must slowly but surely sink. They then collect in the lower part of the lava-column. While still undissolved, they may be erupted along with the fluid lava in which they rest, giving ultra-basic porphyritic lavas; or, as seems more probable, they are slowly dissolved in this lower, hotter part of the lava-column, forming one or more ultra-basic layers which, on injection, crystallize into peridotites or, following extrusion, develop picritic or limburgitic rocks.

The hypothesis is backed up by a comparison of the average olivine basalt and average augite andesite of the world; by a comparison of

the chemical nature of an individual and typical olivine basalt, its phenocrysts and its base; by the fortunate occurrence of simultaneous eruptions from the crater and low-lying lateral fissure at the Réunion volcano where Vélain shows the differentiation has taken place ideally; by the abundant proofs that heavy crystals do and must slowly sink and light crystals slowly rise in lavas, and in rock-melts; by the well-known facts of field-association and bodily development of augite andesite, olivine basalt and ultra-basic rocks throughout the different continents.

If the hypothesis correctly represents the facts and the augite andesites of the sea-floor volcanoes and of so many continental volcanoes are truly derivatives of olivine basalt, we have one more important link in the chain of argument leading to the belief that basaltic magma forms the universal substratum of the earth's crust today and has formed that substratum since Keewatin (early Archean) times. With this conception as a working theory the writer also connects the view that the crust overlying this basaltic substratum is stratified by density, so that the lower layer of the crust is crystallized basaltic magma (gabbro, possibly merging upward into anorthosite) and the upper layer is a composite of dominantly acid material. This latter is considered as made up largely of original granite or gneissic rock, similar to the staple fundamental gneiss of the pre-Cambrian—a layer probably less than thirty kilometers thick. This layer was crystallized in pre-Keewatin time; through it the basic Keewatin lavas were erupted; and through it basaltic magma has, from place to place and from time to time, ever since been erupted. The universal basaltic layer has thus been the effective source of the heat involved in the eruption of post-Keewatin igneous magmas. By the spontaneous differentiation of the primary basalt through fractional crystallization, the few rock-types specially discussed in this paper, have been locally derived. Most of the other eruptive rocks are, on this same working hypothesis, regarded as derived from the formation and differentiation of magmas which are the product of the solution of the acid, original gneissic shell and of its sedimentary veneer in the primary basalt. In other words, both the "syntectic"¹ (assimilation) theory and the fractional-crystallization theory seem to the writer to be essential and principal elements in the final solution of the genetic problem of the igneous rocks.

¹ F. Loewinson-Lessing, *Congrès géol. internat. Compte rendu*, 7th session, St. Petersburg, 1897, p. 375.